

Symmetry and constancy in the perception of negative and positive luminance contrast

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The perception of suprathreshold luminance contrast was investigated by forced-choice psychophysical procedures that were designed to define contrast equivalence relations. Observers compared the perceived contrast of rectangular bars that were presented for 500 msec at 3.9 deg on opposite sides of the fovea. The results show a nearly symmetrical relation between the perception of negative and positive contrast that is largely invariant over four decades of background luminance. Thus, for any fixed background luminance, equal absolute contrasts evoke approximately equal perceived contrasts. Symmetry also held with variations in the width, the eccentricity, and the focus of the bars. Symmetry was investigated further by determining equivalent contrast relations for negative contrasts as a function of background luminance and by contrast scaling. These results show evidence for nearly perfect contrast constancy for targets of low to moderate contrast and departures from constancy for high-contrast targets. These new findings on negative contrast, symmetry, and contrast constancy are discussed in relation to underlying mechanisms for contrast perception and classic experiments on brightness and lightness constancy.

1. INTRODUCTION

Negative luminance contrast conveys a wealth of information in such varied forms as typescript, backlit objects, shadows, and the myriad of objects that reflect less light than their backgrounds. Nevertheless, the perception of negative luminance contrast has not been studied as intensively as that of positive luminance contrast. Thresholds for the detection of decremental stimuli only tap the beginning point of the suprathreshold realm of negative contrast and the associated perceptual continuum that runs from the light gray to deep black. In this paper we explore this suprathreshold realm by obtaining some measurements of the relation between luminance contrast and *perceived contrast*. We define perceived contrast as the *perceived difference* between a target and its background.

Previous measurements that seem most germane to the perception of suprathreshold negative contrast come primarily from studies of simultaneous brightness contrast or brightness constancy in which observers either matched or scaled the brightness of targets appearing on backgrounds of higher luminance.¹⁻¹¹ In this paper we take a somewhat different approach by having observers judge contrast rather than brightness in experiments that are expressly designed to yield contrast equivalence relations.

We start with the premise that observers can judge the relative magnitude of *perceived contrast* independently of the contrast sign. We find that such judgments are relatively easy to make and yield orderly psychometric functions when forced-choice procedures are used. From these functions we have determined *perceptual equivalence relations* between negative and positive luminance contrasts. We then extend the approach to determine perceptual equivalence relations for negative luminance contrasts over a wide range of background luminance. Taken together, our data provide evidence for two properties of contrast perception—symmetry and contrast constancy—that have implications for the

underlying mechanisms of contrast vision and for aspects of classic experiments on brightness and lightness constancy.

2. METHODS

Apparatus

Vertical bars were generated on a Joyce Electronics cathode-ray-tube (CRT) under computer control, as described in detail previously.¹² The screen subtended 8 deg vertically and 13.6 deg horizontally. Luminance was calibrated with a UDT 80X photometer. Adaptation level was varied by placing precisely calibrated neutral-density filters in front of the observer's eye and making fine adjustments in CRT luminance to achieve the exact level desired.

In auxiliary experiments, an optical system containing interference filters (~11-nm bandwidth) and a xenon source was used to generate stimuli for spectral sensitivity measurements. A beam splitter was arranged so that the spectral stimuli appeared as increments on the CRT screen.

Procedure

Contrast Equivalence for Negative and Positive Contrasts

Observers monocularly viewed the display schematized in Fig. 1A while maintaining fixation at the center (*F*). A spatial two-alternative forced-choice procedure was used to assess the perceived contrast of negative and positive contrast bars. On each trial, a standard bar with negative contrast was presented for 500 msec on one side of the fixation mark and a comparison bar with positive contrast was presented simultaneously on the other side. The bars were 1.4 deg × 8 deg (width × height), and their inner edges were 3.2 deg lateral of the fixation mark. The observer was required to press a button to indicate which bar had the greater perceived contrast. After a response, a delay occurred so that about 3 sec

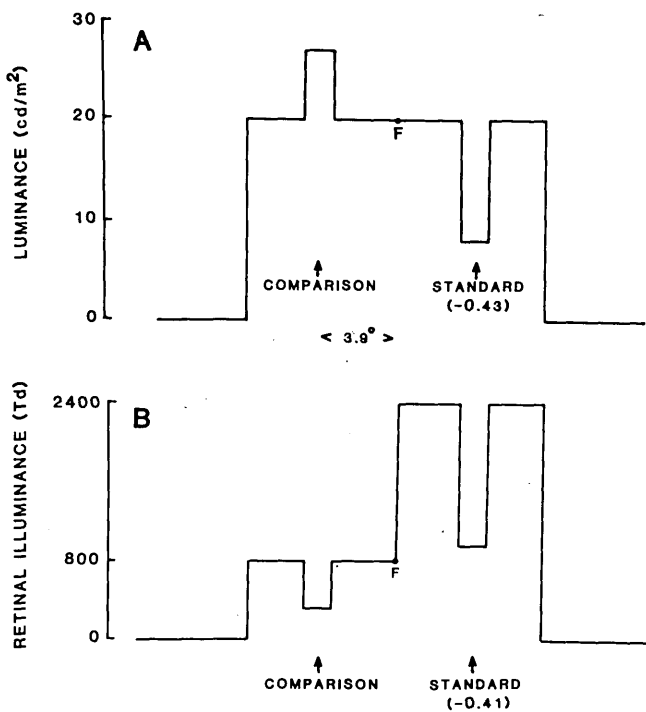


Fig. 1. A, schematic representation of the display used to investigate perceptual equivalence relations between negative and positive luminance contrasts. In the case illustrated, the standard bar is set at a contrast of -0.43 . B, display used to investigate equivalent contrasts for negative luminance contrasts on backgrounds that differ in luminance. In the case illustrated, the standard bar is set at a contrast of -0.41 . Fixation is at F. See text for further details.

intervened between stimuli. Data were collected by the method of constant stimuli, using the following protocol. Each of 6 standard contrasts (-0.05 , -0.15 , -0.29 , -0.43 , -0.56 , and -0.64) was used in combination with an appropriate set of 5 comparison contrasts, yielding a total of 30 standard/comparison combinations, each of which was presented 30 times in a single session. The order of presentation of the pairs and the side on which the standard appeared were randomized by the computer. In separate sessions, the background luminance was set at different fixed levels, ranging from 0.017 to 200 cd/m^2 . The observers adapted to the background for at least 10 min before trials were initiated.

Twenty additional sessions were run to investigate the effect of variations in several stimulus parameters: (1) Bar separation was reduced to 0.3 and 2.0 deg (distance between the inner edges of the bars) with background luminance set at 200 cd/m^2 . (2) Bar width was reduced to 0.15 deg with the background luminance at either 200 or 1.55 cd/m^2 . (3) The effect of defocus was studied by placing a $+2.5$ -D lens in front of the eye while the observers viewed the standard display of Fig. 1A with background luminance at 200 or 1.55 cd/m^2 . (4) The effect of the luminance profile was studied by presenting decremental bars with a cosine luminance profile (1.4 -deg half-cycle width) and the usual set of square incremental comparison bars on a background luminance of 200 cd/m^2 .

In all experiments, contrast is specified as $(L_{\text{max}} - L_{\text{min}})/(L_{\text{max}} + L_{\text{min}})$. In the case of incremental bars, L_{max} and L_{min} are the bar and background luminance, respectively. In the case of decremental bars, L_{max} is the

background luminance and L_{min} is the bar luminance, and a minus is prefixed to indicate the contrast polarity.

Equivalent Contrasts for Dark Bars Viewed on Different Backgrounds

The object of this experiment was to determine equivalent contrast relations for dark bars viewed on backgrounds that differ in luminance. The psychophysical procedures were fundamentally similar to those described above for comparing negative and positive contrasts. The display consisted of two adjacent background fields whose luminance differed by a factor of 3.0, as schematized in Fig. 1B for the specific case in which the backgrounds were set at 2400 and 800 Td. On each trial, a dark bar (1.4 deg in width, inner edge 3.2 deg from fixation) was presented simultaneously for 500 msec on each background. The observer was required to indicate which dark bar had the greater perceived contrast. Each of 6 standard negative contrasts was used in combination with an appropriate set of 5 comparison negative contrasts, yielding a total of 30 standard/comparison combinations and 900 trials per session. The data yielded six psychometric functions whose 50% points defined a total of six pairs of equivalent contrasts. The six paired values were then plotted in a graph with axes of contrast on 800 Td versus contrast on 2400 Td. A contrast-linking function was then constructed by connecting the plotted points with straight lines (i.e., no best-fit procedures were used). From these lines, the value of contrast on 2400 Td, which is perceptually equivalent to any specific value of contrast on 800 Td, can be determined.

In successive sessions, the luminance of the entire display was progressively decreased by a factor of 3.0, and the experimental and analytical procedures were repeated. A total of 10 contrast linking functions was therefore obtained. Since the luminance of the less intense background in one session was equal to that of the more intense background in the successive session, each linking function shared a common background level with one other linking function. Hence, by assuming transitivity from one linking function to the next, equivalent contrasts over the entire range of background luminance could be calculated. For example, for observer DB, linking function 10 indicated that a -0.52 contrast on 0.33 Td was equivalent to a -0.49 contrast on 1 Td, and linking function 9 indicated that a -0.49 contrast on 1 Td was equivalent to -0.48 contrast on 3.3 Td. By transitivity, it then follows that -0.52 contrast on 0.33 Td is perceptually equivalent to -0.48 contrast on 3.3 Td. Continuing such paired comparisons across all 10 linking functions yielded a set of 10 perceptually equivalent contrasts starting at -0.52 on 0.33 Td and ending at -0.35 on 2400 Td. These contrast values were then plotted against background luminance, and a smooth curve was drawn through the data to define an equivalent contrast contour. Additional contours were then determined by starting the analysis at other levels of contrast.

Since the method can accumulate small differences or calibration errors into spurious trends, contrasts were carefully calibrated, equivalents were estimated to three places, and two complete sessions were run for each background pair. The final results summarized below are based on about 18,000 judgments per observer.

To satisfy the transitivity operation, it is necessary that threefold steps in background luminance always produce exactly threefold steps in retinal illuminance. An artificial

pupil (2.75-mm diameter) was therefore used in all these experiments, and background levels are specified in trolands. Natural pupils were used in all other experiments, in which the background luminance is given in candelas per square meter. In the part of the results that involve calculations using data combined from both classes of experiment, we have used the troland-candella-per-square-meter conversion of Wyszecki and Stiles.¹³ Two of the authors served as the observers for all the contrast equivalence experiments.

Magnitude Scaling of Perceived Contrast

Contrast-magnitude data were obtained for decremental bars (1.4 deg in width, inner edge 3.2 lateral of fixation, 500-msec duration) viewed monocularly on a background of 200 cm/m^2 . On each trial, a bar appeared to the right and to the left of fixation. The right bar was of fixed contrast (-0.24) and served as the standard. The contrast of the left bar varied from trial to trial. Eight naive observers were required to estimate numerically the magnitude of the perceived contrast of the left bar relative to the right. They received written instructions and were allowed to select any desired number to represent the perceived contrast of the standard. Bars of -0.45 and -0.095 contrast were shown as examples before the experiment proper began, but no numerical values were given at this stage or in the instructions. After these preliminaries, each observer was presented with a set of 12 contrasts, each repeated 4 times. The order was random except for two constraints: (1) The first trial could not be one of the two highest or lowest contrasts. (2) All 12 stimuli were presented before the next repetition of the set. Numerical estimates were entered on a keyboard and a 2-sec interval occurred before the next stimulus, so the interstimulus interval ranged from about 5 to 8 sec. Data were analyzed by the procedure described previously.¹⁴

3. RESULTS

Equivalence Relations for Negative and Positive Contrasts

Figure 2 shows results obtained for one observer in a single session in which the contrast of dark and light bars was compared, using the protocol described in Section 2 with the background luminance set at 17.4 cd/m^2 . The number to the right of each psychometric function gives the contrast of the standard (dark) bar. The abscissa gives the contrast of the comparison (light) bar. As the contrast of the light bar increases, there is a progressive increase in the percentage of trials on which it is reported as having the greater perceived contrast. At the 50% point on such functions, the dark and the light bars would each be reported to have the greater perceived contrast on an equal number of trials. This specific pair of stimuli may therefore be operationally defined as having *perceptually equivalent contrast*. Such equivalent-contrast pairs are determined from each psychometric function in Fig. 2, by interpolating to find the values on the abscissa (arrows) that correspond to the 50% point on the ordinate.

The orderly form of the functions of Fig. 2 is representative of all results for both of our observers. Thus, by using our forced-choice procedures, observers make consistent judgments. Hence relatively precise estimates of contrast equivalence between decremental and incremental stimuli can be obtained. However, the estimates are less precise for

higher levels of contrast since, as Fig. 2 shows, the slope of the psychometric function decreases with an increase in the level of the standard contrast.

Contrast-equivalence relations were investigated at five background levels, ranging from 0.017 to 200 cd/m^2 . Figure 3 summarizes results for observer DB. The contrast of the standard dark bar is given on the abscissa. The perceptually equivalent contrast of the light bar is given on the ordinate. The data fall close to the diagonal line that is the locus required for an exact equivalence in the absolute value of the contrast. Similar results were obtained for observer JG. Thus, to a good first approximation, our results indicate that, when viewed on the same background luminance, equal absolute luminance contrasts produce equal perceived contrasts. This relation between negative and positive contrasts is called symmetry.

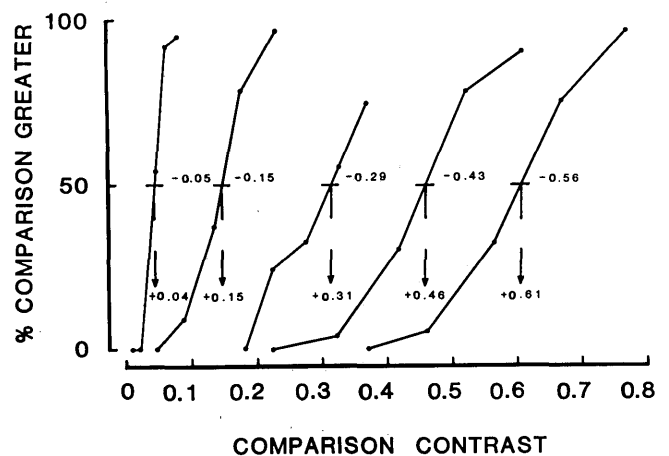


Fig. 2. Psychometric functions for judgments of the perceived contrast of light and dark bars. Number to the right of each curve gives the luminance contrast of the standard dark bar. The projection of the 50% point to the abscissa (arrow) defines the luminance contrast of the comparison light bar that is judged perceptually equivalent to the standard dark bar. Observer DB.

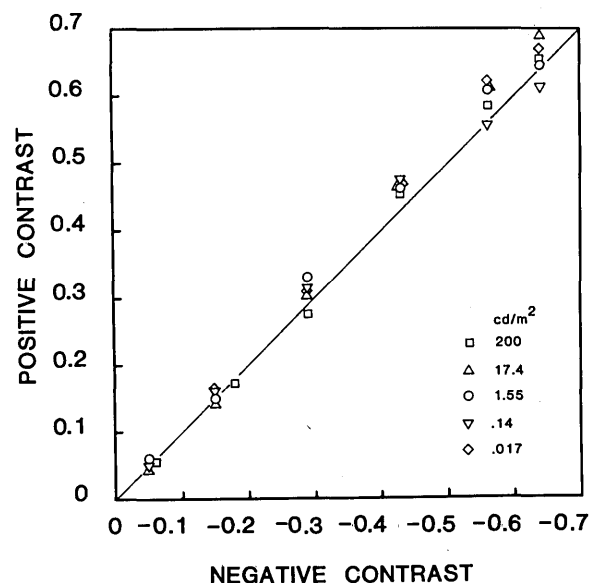


Fig. 3. Contrast-equivalence relations between negative and positive luminance contrasts. Different symbols show results obtained on various background luminances as indicated in the key at right. Observer DB.

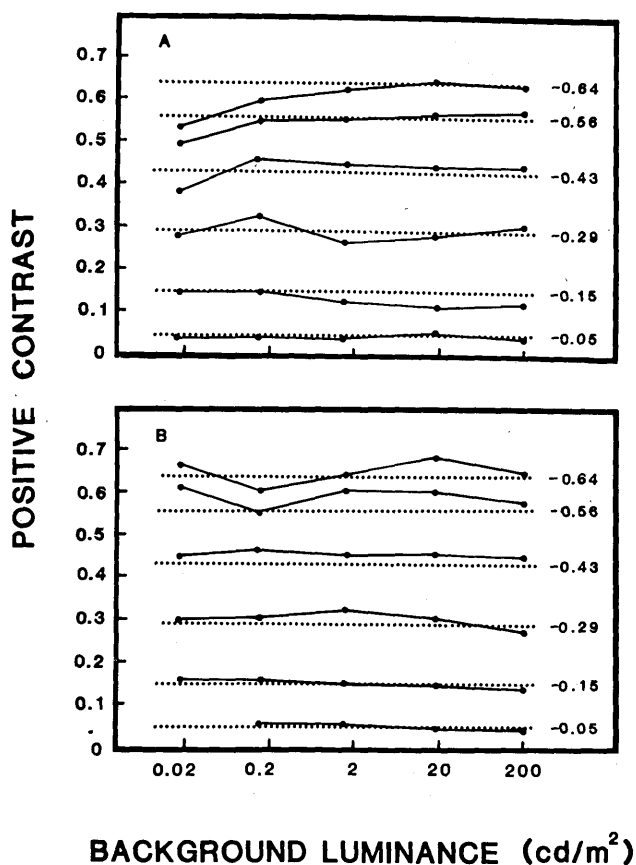


Fig. 4. Contrast equivalence as a function of background luminance for observers JG (upper panel) and DB (lower panel). The numbers to the right give the contrast of the standard (dark) bars. The horizontal dotted lines define the loci for exact symmetry between negative and positive contrasts (see text).

Symmetry is somewhat dependent on the metric used to specify contrast. Over the range of our data, the $(L_{max} - L_{min}) / (L_{max} + L_{min})$ definition (Michelson contrast) is approximately equal to the absolute value of the common logarithm of T/B , where T is the target luminance and B is the background luminance. For our data, symmetry will therefore hold about equally well for either definition of contrast. However, if contrast is defined as $\Delta L/L$, where ΔL is the size of the luminance step from the background luminance L , our data describe a decidedly asymmetric relation in which positive contrast is considerably less effective than negative contrast. For measurements of contrast-increment thresholds for flashes exceeding the critical duration, Legge and Kersten¹² report a similar result: Measurements for light and dark bars are nearly coincident when plotted as Michelson contrast but clearly diverge when plotted in units of $\Delta L/L$.

Figure 3 indicates that the symmetry between negative and positive contrasts is largely invariant with background luminance. To show this more clearly, all the data for both observers are plotted as a function of background luminance in Fig. 4. The ordinate gives the values of positive contrast that are judged perceptually equivalent to each of the standard negative contrasts whose values are shown at the far right. In this format, the data will lie along a set of horizontal lines if contrast-equivalence relations are invariant with background luminance. For the specific case of symmetry, the data should

fall on the specific set of dotted horizontal lines shown in Fig. 4. The departures from the dotted lines are not large or clearly systematic when examined across both observers and the greater variability of the high contrast determinations is considered (see above). Thus, under the present conditions, we conclude that the relation between negative and positive contrasts is nearly symmetrical and largely independent of background level.

The invariance of symmetry led us to perform auxiliary experiments to determine how other aspects of parafoveal vision were affected by background luminance over the same range as that of Fig. 4. Our findings were as follows: (1) Contrast thresholds for dark and light bars changed by about a factor of 7. (2) The spatial contrast sensitivity function showed marked changes in form, maximum sensitivity, and high-frequency cutoff. (3) For backgrounds down to about 4 cd/m^2 , the relative sensitivity ratio for the detection of 590- and 500-nm incremental flashes remained at the value expected for photopic vision (about 2.0) but then progressively dropped to 0.35 at 0.04 cd/m^2 . (A value of about 0.1 is expected for pure scotopic vision.) Thus other aspects of parafoveal vision show appreciable changes with background luminance, whereas the symmetry between negative and positive contrast remains largely invariant.

Effects of Spatial and Optical Variables

The effects of several stimulus variables on contrast equivalence were explored in further experiments. The lateral separation of the bars, 6.4 deg (inner edge to inner edge) in the main experiments, was reduced to 2.0 and 0.3 deg. The effect of reducing the bar width from 1.4 to 0.15 deg was also investigated. Figures 5A and 5B show that these variations pro-

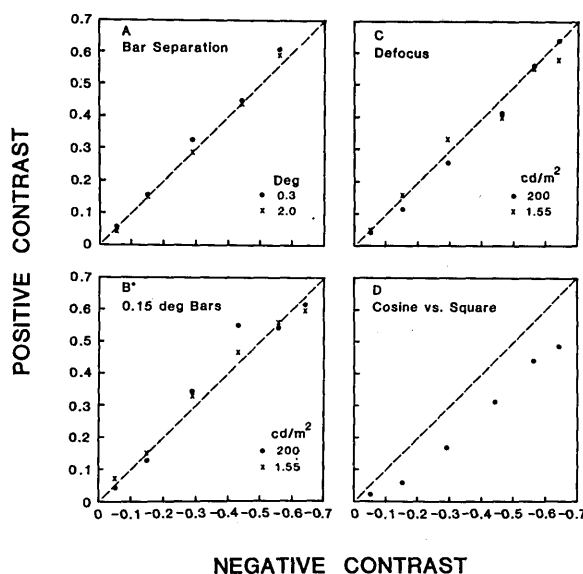


Fig. 5. Effects of stimulus variables on equivalent-contrast relations between negative and positive contrast. A, data for bars whose inner edges were separated by 0.3 and 2.0 deg. Background luminance: 200 cd/m^2 . B, data for 0.15-deg bars on backgrounds of 200 and 1.55 cd/m^2 . C, effect of placing a +2.5-D lens in front of the eye with background luminance set at 200 and 1.55 cd/m^2 . D, comparison of dark bars with a cosine luminance profile (abscissa) versus light bars with a square profile (ordinate). Background luminance: 200 cd/m^2 . See text for details. In B, C, and D, the distance between the inner edges of the bars was 6.4 deg. The results in this figure for observer JG were confirmed in identical experiments for observer DB.

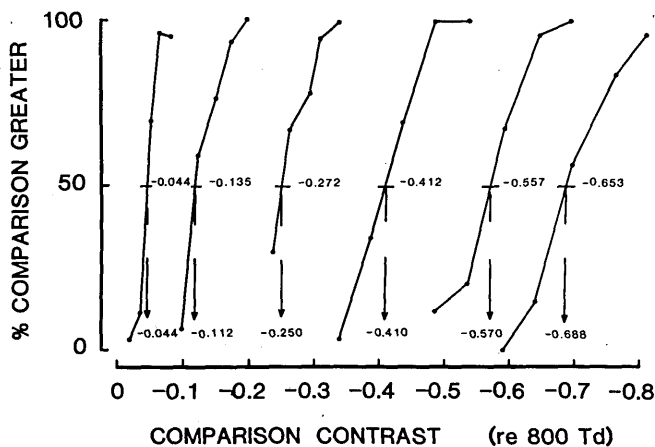


Fig. 6. Psychometric functions obtained in a single session in which standard and comparison bars were presented on backgrounds of 2400 and 800 Td, respectively. The number to the right of each psychometric function gives the luminance contrast of the standard bar on 2400 Td. The projection of the 50% point to the abscissa (arrow) defines the luminance contrast on 800 Td, which is perceptually equivalent to the standard bar on 2400 Td. Observer DB.

duced no substantial departures from symmetry. Figure 5C shows that symmetry also continued to hold when marked defocus was produced by placing a +2.5-D lens in front of the eye while the observer viewed the standard display of Fig. 1A.

In a further variation, light bars with the usual square profile were compared with dark bars having a half-cycle cosine luminance profile (1.4 deg). Figure 5D shows that the data lie consistently below the symmetry locus. Thus, if a cosine bar and a square bar are equated for luminance contrast, the perceived contrast of the square bar is greater than that of the cosine bar.

The perceived contrast of in-focus square bars should also be greater than that of defocused square bars, since defocusing a square bar will produce a quasi-cosine luminance profile on the retina. Thus the finding that contrast equivalence plots for in-focus or defocused bars appear virtually indistinguishable (Fig. 3 versus Fig. 5C) illustrates that our contrast-equivalence measurements give no information about sensation magnitude. Therefore, our main results (Figs. 3 and 4) indicate that the relation between positive and negative contrasts is approximately invariant but do not rule out the possibility that the magnitude of perceived contrast may be changing significantly with changes in background luminance. The remaining experiments were designed to pursue this issue.

Equivalent Contrasts for Dark Bars on Backgrounds That Differ in Luminance

The display consisted of two adjacent background fields whose luminances differed by a factor of 3.0. A dark bar was simultaneously presented for 500 msec on each background, and the observer was required to indicate which bar had the greater contrast. The procedure is fully described in Section 2.

Figure 6 shows psychometric functions obtained in a single session in which a series of standard bars was presented on a 2400-Td background and comparison bars were presented on a background of 800 Td. The number to the right of each

psychometric function gives the contrast of the standard bar. The projection of the 50% point to the abscissa (arrows) defines the perceptually equivalent contrast on the 800-Td background. The orderly nature of the psychometric functions of Fig. 6 is representative and provides evidence that observers can make such judgments with reasonable precision. In successive sessions, the basic procedure was repeated for threefold stepwise reductions in the luminances of both background fields. As described in Section 2, the data were then used to determine equivalent contrasts over some four decades of background luminance.

Figure 7A shows results for observer DB. The smooth curves are drawn by eye. Each curve defines an equivalent-contrast contour. That is, according to our rationale and measurements, all contrast values that lie on a given curve produce perceptually equivalent contrasts. The three lower curves rise as background luminance increases. Thus, to produce perceptually equivalent contrasts, larger luminance decrements are required on the lower rather than on the higher backgrounds. The three upper curves are virtually horizontal, indicating that no appreciable change in luminance contrast is required to maintain a constant perceived contrast. Figure 7B shows similar results for JG. The main difference between observers occurs at low backgrounds for low contrasts (<0.30), where the data for JG show some downturn. In general, these results suggest that, for low to moderate luminance contrasts, the magnitude of perceived contrast is relatively constant with changes in background luminance, whereas, at higher luminance contrasts, there are measureable departures from constancy. To put these departures in perspective, it is necessary to know how the magnitude of perceived contrast is quantitatively related to luminance

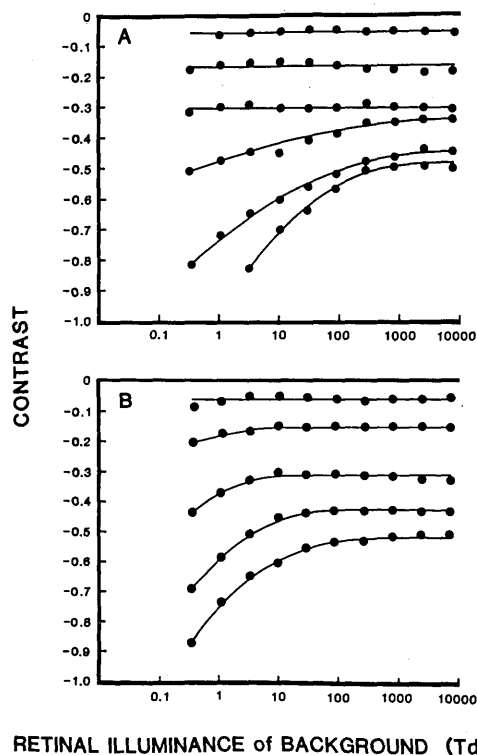


Fig. 7. Equivalent-contrast relations for negative luminance contrasts as a function of background luminance. A, observer DB. B, observer JG. The smooth curves, drawn through the points by eye, define equivalent contrast contours.

contrast. The next experiment is designed to provide this information.

Scaling of Negative Contrast

Magnitude estimates of the perceived contrast of dark bars on a background of 200 cd/m^2 were obtained as described in Section 2. The filled circles in Fig. 8 show the geometric mean data for eight naive observers. The smooth curve is the least-squares best-fitting power function: $P = 100 \times C^{0.83}$, where P is the magnitude of the perceived contrast, C is the absolute value of the luminance contrast, and the coefficient of 100 is arbitrarily selected so that P is 100 when $C = 1.0$. The open circles show data for observer DB. They do not differ appreciably from the mean data for naive observers. For the analysis that follows, we take the smooth curve as the best estimate of the relation between perceived contrast magnitude and the luminance contrast of dark bars viewed on a 200-cd/m^2 background. By using this curve as a reference, we can now use contrast equivalence measurements to calculate the magnitude of the perceived contrast evoked by both negative and positive luminance contrasts when viewed on other background luminances. The results of such calculations, based on the data for observer DB (Figs. 3 and 7A), are shown by the symbols in Fig. 9. Similar results were calculated for observer JG.

The smooth curve without symbols at the top left of Fig. 9 is the reference curve taken from Fig. 8. The other curves are drawn by eye near the appropriate symbols. The similar form and range of the curves for negative and positive contrasts at any given background are a consequence of the symmetry relation found in Fig. 3. The approximate coincidence of the symbols and the use of a single smooth curve over the low-to-moderate-contrast range in Fig. 9 is a consequence of the approximate constancy (i.e., horizontal contours) found in Fig. 7. The divergence of the curves in the upper-contrast range in Fig. 9 is a consequence of the divergence of the high-con-

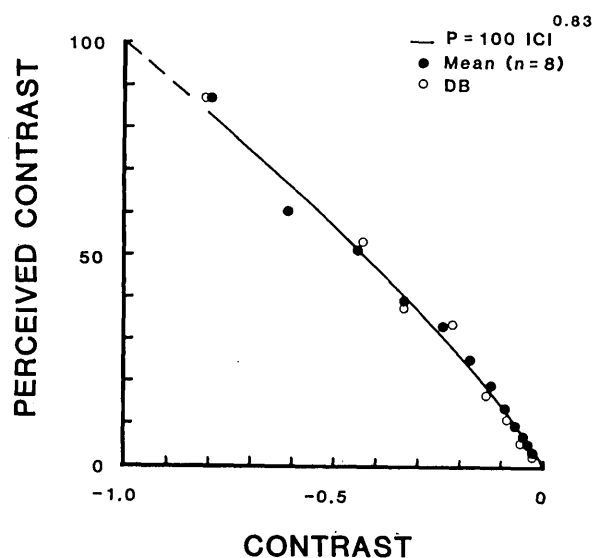


Fig. 8. Magnitude estimation of the perceived contrast of dark bars presented on a background of 200 cd/m^2 . Filled circles show mean data for eight naive observers. Open circles show data for observer DB. The smooth curve is the best-fitting power function given at the top of the figure.

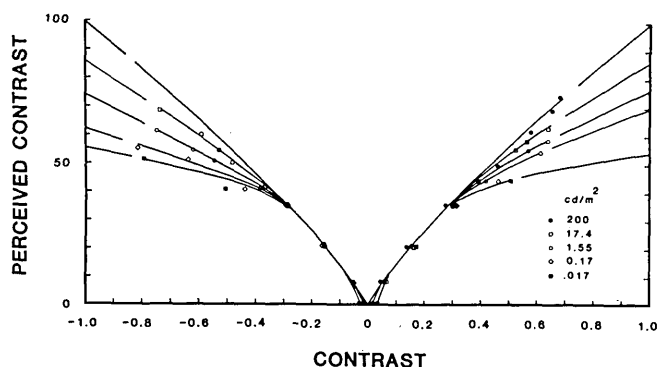


Fig. 9. Relation between perceived contrast and luminance contrast for bars viewed on various background luminances. The top left smooth curve is based on the equation given in Fig. 8. The other curves are drawn by eye. They are interrupted where the data end and then extrapolated to cover the entire contrast range. Observer DB. See text for further details.

trast contours found in Fig. 7. The divergence of the curves near zero contrast is a consequence of variations in detection thresholds with background luminance, which were measured in auxiliary experiments.

5. DISCUSSION

We investigated the relation between negative and positive contrast by the determination of equivalent contrasts and found a simple relation that we have called symmetry. Symmetry is at odds with the hypothesis that equivalent contrasts are produced by targets that produce equal decrements or increments in luminance (ΔL) relative to the background. In the format of Fig. 3, this hypothesis predicts a smooth, negatively accelerated curve that asymptotes at $+0.33$ contrast and thus lies significantly below the symmetry locus. Thus symmetry seems a sufficiently distinctive finding to place some quantitative constraints on models for the underlying mechanism of contrast vision.

Electrophysiological recordings from neurons in the monkey LGN¹⁵ and cones in the fish retina¹⁶ indicate that these cells generate approximately equal absolute changes in response to equal contrasts of opposite sign, provided that the background luminance is not too low. A similar result is implicit in the model and data for cone light adaptation presented by Dawis and Purple.¹⁷ These physiological observations may provide a neuronal basis for symmetry, if the sign of the response is ignored or rectified at later stages of the system. However, in all the physiological data, symmetry breaks down at low background luminances. Negative contrasts are then less effective than their positive counterparts. On these and more-general grounds, we expect a similar breakdown in human vision at low background luminances. The failure to find clear evidence for this in Fig. 3 is probably explained by the fact that the lowest backgrounds, although dim, were still some 2–3 log units above absolute threshold.

In some respects, the conditions of our experiments of Fig. 1B resemble those of classic brightness-matching experiments, but there are also fundamental differences. We have used discrete presentations (500 msec) and forced-choice matching procedures. Our step-by-step procedure allowed us to derive equivalent-stimulus relations over some four decades of lu-

minance, although the procedure required only that the observers make direct comparisons in the presence of modest (threefold) differences in background luminance. Our observers judged the perceived contrast rather than the brightness of a target. Although a comprehensive discussion of the distinction between contrast and brightness falls beyond the scope of this paper, we wish to emphasize two points: (1) There are data to support this distinction.^{9,18} (2) It is our working hypothesis that brightness and contrast are only partially correlated dimensions and that the degree of correlation may vary markedly with stimulus conditions and the procedures used to measure brightness and contrast.

There are some qualitative parallels between our data of Fig. 7 and those of brightness-matching experiments, as would be expected if brightness and contrast are partially correlated under these conditions. Our data indicate that almost perfect constancy will be observed if measurements are made for decremental targets over a restricted range of relatively high background luminance. These are the essential conditions and results of the often-cited brightness constancy experiments of Wallach.² For sine-wave gratings, Kulikowski¹⁹ reported evidence previously for contrast constancy over a modest range of contrast and background luminance that falls within the constancy region of Fig. 7. For larger ranges of background luminance and moderately high contrasts, Figs. 7 and 9 show clear departures from constancy that are in the same direction as those found in previous work involving brightness matching or scaling.^{1,3,5,7-9}

Differences in the response indices and the state of adaptation preclude quantitative comparison between our contrast scaling results of Fig. 8 and past work on brightness scaling of decremental stimuli.^{5-8,10} For sine-wave gratings, Gottesman *et al.*¹⁴ found that perceived contrast grew as a power function of luminance contrast with an exponent of about 0.7, which is close to the value of 0.83 found here. The contrast/response functions of cortical neurons in cat and monkey show considerable variation in detail from cell to cell.²⁰ Thus the results of Fig. 8 probably reflect the composite response of a population of neurons whose members differ in the quantitative form of their response to negative contrast.

The phenomenon that some aspect of the appearance of achromatic objects tends to remain relatively constant with changes in the ambient illumination has been analyzed in some detail since it was first highlighted by Hering.^{2-5,11,21-25} However, the literature on constancy is plagued by at least three problems: (1) The perception of achromatic targets is multidimensional,^{8,9,18,21,23} so it is likely that the estimation of constancy will vary appreciably with the response dimension (brightness, relative brightness,⁸ lightness, perceived contrast) and experimental measures selected for analysis. (2) Although it is often held that luminance contrast is the fundamental stimulus dimension, the procedures used in some classes of constancy experiments^{5,8,22,23,25} involve inherent ambiguity about the background luminance, so the stimuli cannot be specified in luminance contrast. (3) Although it is widely recognized that constancy is not perfect, the magnitude of the actual departure from constancy is difficult to evaluate because of the limited range of background luminance used in some studies and because of inherent limitations of both matching data and interval scales (*viz.*, the lightness scale) for obtaining estimates of response magnitude.

The present work may provide some new purchase for further evaluating the constancy phenomenon. First, our procedures were designed to assess perceived contrast, and we suggest that this may be the appropriate response dimension for the constancy phenomenon that Hering had in mind. Second, our stimuli are specified in luminance contrast, and, since our equivalence data span a large range of background luminance and are supplemented by scaling measurements, departures from constancy can be assessed. Thus, at the extremes, the extrapolations of the curves in Fig. 9 indicate that there is only about a twofold change in perceived contrast over about a 10,000-fold change in background luminance. Therefore, for the dimension of perceived contrast, it appears that the visual system does, in fact, come remarkably close to maintaining constancy under the conditions studied in this paper. Furthermore, even when departures from constancy occur, the results of Fig. 3 indicate that symmetry between positive and negative contrasts is maintained.

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